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IAEA INTOR WORKSHOP REPORT, GROUP 4

——HEATING——

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IAEA INTOR Workshop Report, Group 4
— Heating —

Fusion Research and Development Center,
Tokai Research Establishment, JAERI

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Data base assessments of additional heating system and heating physics for INTOR tokamak were made. This report covers neutral beam injection and radiofrequency heating.

Keywords: INTOR Tokamak, Additional Heating, Neutral Beam Injection, Radiofrequency Heating, Data Base Assessment

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－加　熱－

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INTORトカマクの第二段加熱装置と加熱の物理についてデーターベースの評価を行った。本報告では，中性粒子入射と高周波加熱について言及している。

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1. Introduction

(1) Power Requirement

From a power balance consideration, the heating power required for achieving the ignition conditions ($\bar{n}\tau_E = 2\times10^{20}\ \mathrm{m}^{-3}\cdot\mathrm{s}$ and $\bar{T} = 10$ keV) is given by

$$P = \frac{2\times10^{8}}{\tau_E^{\,2}} \qquad \text{(watts)}$$

in INTOR. Providing that $\tau_E = 1.7\sim2$ sec and $\bar{n}_e = 1.2\times10^{20}\ \mathrm{m}^{-3}$, the approximate power becomes $P = 50 \sim 70$ MW (see Group 1).

(2) Beam Energy for Neutral Beam Injection

When the impurity concentration is sufficiently small ($Z_{eff}\sim1$), the beam energy permiting effective neutral beam injection (NBI) heating without surface trapping of the beam is approximately given by

$$E_b \gtrsim 9\times\bar{n}_e\ (10^{20}\ \mathrm{m}^{-3})\ A_b\cdot L \quad ,$$

where A_b is the atomic number of the beam particles and L the beam pass between the plasma surface and the plasma center. By choosing the quasi-perpendicular injection scheme, E_b becomes about 250 keV at $\bar{n} = 1.2\times10^{20}\mathrm{m}^{-3}$. If the major component of the beam is envisaged to become larger than 75%, the 200 keV deuterium beam can be used in INTOR (see Group 1).

Because the Joule plasma densities might be $2\sim3\times10^{19}\ \mathrm{m}^{-3}$, another beam injection with a lower energy (E_b = 100 keV) and low power of about 10 keV may be required for low density plasma heating.

(3) Wave Heating

Five kinds of wave heating methods can be considered for INTOR. Typical aspects of these methods are summarized in Table 1.

Shear and compressional Alfvén wave heating techniques are possibly used in a large scale tokamak such as INTOR operated at high densities, and furthermore the high power wave generator technology has been established. On the other hand, they are lack of effectiveness proof and have an essential demerit of mounting an antenna inside the vacuum vessel.

Electron cyclotron resonance heating (ECRH), which is useful for profile control, requires significant progress in high power high frequency generator development.

Ion cyclotron range of frequencies (ICRF) is supported by the established generator technology and the many experimental trials. Although effective ion heating has been observed, deleterious effects caused by impurity inflow have usually influenced the plasma behavior. In the application of ICRF to INTOR, a waveguide should be employed as the wave launcher. Then the effective coupling by matching the eigenmode resonance conditions can not be expected and the ion-ion hybrid resonance scheme becomes important. In this situation the control of ion species is essential, but the ion species in the INTOR plasmas must be defined so that the fusion burning is in the optimum condition.

The lower hybrid heating has been demonstrated successfully in some tokamak devices. Although the detailed understandings of the wave propagation and heating mechanisms have not been obtained until now, no significant technological difficulty is accounted. Hence it is considered that the LHH scheme is preferable as the wave heating method in INTOR.

Table 1 Wave Heating Aspects for INTOR

	Frequency	Launcher	Generator Technology	Experimental Proof
Shear Alfvén Wave Heating	2-3 MH$_z$	Complex antenna	available	few
Compressional Alfvén Wave Heating	2-5 MH$_z$	Simple antenna	available	few
ICRF	25-75 MH$_z$	Wave guide	available	successful
LHRF	2.5-3 GH$_z$	Wave guide	available	seccessful
ECRH	140 GH$_z$	Wave guide	Not available	successful

2. Assessments for INTOR Workshop

2.1 Neutral Beam Injection

2.1.1 Additional Experimental Basis

The experimental basis for high power quasi-perpendicular injection is not sufficient until now. Hence some additional experiments are essentially required concerning the perpendicular injection of intense neutral beams into a large tokamak such as JT-60 from a view point of excitation of beam instabilities (ion cyclotron instability, lower hybrid instability, Alfvén wave instability etc.)

Another problem comes from the beam attenuation by high-Z impurity ions. Because the ionization cross-section and the charge-exchange cross-section have not been understood sufficiently for the high-z impurities, detailed atomic data should be accumulated.

2.1.2 Beam Penetration

The deuterium beam with the energy of 200 keV can be used in INTOR for parameters: $a = 1.2$ m, $\overline{n} = 1.2 \times 10^{20}$ m^{-3} and $Z_{eff} = 1$, even when the quasi-perpendicular injection geometry is employed. The fraction of energy components with 200 keV must be as large as 75%.

2.1.3 Ripple Injection

It is concluded from the following considerations that ripple injection can not be appropriate in INTOR. The ripple trapping condition is given by

$$\delta_{eff} < \frac{b}{2v_d} \frac{1}{\tau_D}$$

where δ_{eff} is the ripple well depth, v_d ($= E_0/eRB$) the $\nabla \vec{B}$ drift velocity, τ_D the 90 degrees scattering time and b the elongated minor radius of the plasma cross-section. The relation between the ripple well depth δ_{eff} and the toroidal magnetic field ripple δ is given by

$$\delta_{eff} = 2\delta - \frac{r}{R_0} \frac{\pi}{qN} ,$$

where q is the safety factor at the minor radius r, N the toroidal coil number and R_0 the major radius. Then the toroidal field ripple required becomes

$$\delta = \frac{b}{4} \frac{1}{v_d \tau_D} + \frac{r}{2R_0} \frac{\pi}{qN} \quad .$$

When it is taken that $q \sim 1$, $N = 16$, $n \sim 1 \times 10^{20}\ m^{-3}$, $E_b = 200$ keV and $r \sim 1$ m, δ must be as large as 2%. To form a ripple field of about 2% near the plasma center, the ripple field at the plasma boundary $(r \sim b)$ reaches several to ten percents.

In the meanwhile, banana particles untrapped in the ripple field are driven radially due to the asymmetric field strength at the turning points. The outward velocity of these particles is

$$\langle v_r \rangle = \frac{\sqrt{2}}{\pi} \frac{\delta_{eff}}{\varepsilon} v_d \quad ,$$

where ε is the inverse aspect ratio. The INTOR parameters and the value of δ_{eff} defined above predict $\langle v_r \rangle \sim 30$ m/s. This banana drift velocity is too large for the fast ion confinement: the fast ion confinement condition $a/\langle v_r \rangle \ll \tau_s$ can not be satisfied, where a is the minor radius and τ_s the fast ion slowing-down time.

2.1.4 Technological Assessment of Neutral Beam Injection

a. An injector used in a reactor environment

- The neutral beam injector without magnet systems between ion source and neutralizer would be appropriate for INTOR.

The reason are;

(1) We understand that at this time there is a lack of appricable data on the damage of materials used in ion sources due to neutron irradiation. Therefore, it is premature at present to reject the injector without magnet systems.

(2) A configuration with magnet systems would be a complicated system. The system shall produce magnetic field in the ion bending region while shield both ion source and neutralizer. The ion bending path shall be small with a low vacuum pressure to suppress power loss of ions due to unfavolable neutralization. A beam dump for escaping neutralized beams shall also be provided.

Since there is no ample reason to reject injector without magnet systems at present bases, we would choose a design without magnet systems unless protection of the ion source due to neutron irradiation revealed to be impossible. Once the reliable data on the neutron damage are obtained, the life of the ion source shall be evaluated on some specific beam line designs.

b. Neutral beam power density

- Neutral beam power density of 3 - 5 kW/cm^2 will be delivered in INTOR.
- Design value of the power density of the JT-60 neutral beam system (20 MW, 75 keV, 10 sec) is about 0.7 kW/cm^2.(1,2) We are now determining final specifications of the prototype unit of the JT-60 neutral beam system, and the order will be placed in the summer of 1979. Further, we are planning an upgrade neutral beam system, where the power density of the neutral beam is about 1.4 kW/cm^2.
- A design value of the power density of the 1 MW neutral beam system for JFT-2 (30 keV, 50 msec) is about 5 kW/cm^2. This system is under construction and will be completed in the beginning of 1980.
- The power density of long pulse injectors is smaller as compared with that of short pulse injectors mainly due to the following reasons;
  (1) a large beam dump and a large beam target is required to handle large heat loading,
  (2) transparency of the beam extraction grids shall be limited to yield a sufficient space for cooling of the grids.

c. Beam species

- We envisage the fraction of ion species D^+: D_2^+: D_3^+ to be about 90: 7: 3 by the INTOR construction phase. If this ratio can be achieved, the fraction of the neutral energy components D^0(200 keV): D^0(100 keV): D^0(67 keV) becomes 75: 16: 9 for 200 keV D^+ beams with 90 % equilibrium cell.
- In the JT-60 neutral beam system, design values of the ion species and the beam energy components are as follows;(1,2)

  H^+: H_2^+: H_3^+ = 75: 20: 5 (standard beam energy of 75 keV),
  H^0(75 keV): H^0(37.5 keV): H^0(25 keV) = 58: 32: 10
  (90 % equilibrium cell).

d. Neutral beam efficiencies of an INTOR injector

We estimate the overall power efficiency of a 200 keV INTOR injector under the assumptions shown in Table 2

Grid heat load is assumed from the experimental results of two stage acceleration of 75 kV at JAERI$^{3)}$. Estimate of backstream electron and secondary ion loss will be shown in other report$^{4,5)}$ (see Sec. 3. (1) of this report). Neutralization efficiencies are calculated in the case of 90 % equilibrium neutralizer cell using the cross section data compiled by C. F. Barnett et al.$^{6)}$ Reionization loss and beam divergence loss is calculated from those values in Engineering Aspects of JAERI Proposal for INTOR (II).

The calcurations are shown in Figs.1 and 2. Table 3 shows the overall power efficiencies.

e. Necessity of a direct energy converter

- A direct converter will be necessary in the INTOR.
- With an use of the direct converter, a heat load on a beam dump decreases, and the overall efficiencies of the injector increases significantly. The latter will save not only the electric power capacity, but the initial investment for the beam power supply.
- By using the direct converter, the heat load on the beam dump will be reduced to be level of 200 w/cm^2.
- In the JT-60 injector without the direct converter, the maximum heat load on the beam dump are designed to be about 500 w/cm^2.

f. Reliability of the INTOR neutral beams

- Major difficulties will be in the cooling problems of the beam dump, the beam target, and the ion source. However, these problems will be solved in the JT-60 developmental stage, and no essential problems will be left from the thermal view point.
- The pulse length and the duty factor of the JT-60 injector are 10 sec and 1/30, respectively.

g. Pumping problems

- Main problems are as follows;
  (1) Pumping of an ion extraction region and an adoption of new neutralizing method such as gas jet stream.

Table 2 The assumptions for estimation of the overall power efficiency of a 200 keV INTOR injector

1. Acceleration region loss	
(1) Grid heat loss	8 %
(2) Backstream electron and secondary particle loss	6 ~ 18 %*
2. Species mix	
$D^+ : D_2^+ : D_3^+ = 90 : 7 : 3$	
3. Neutralization efficiency	
for D^+	18.2 %
for D_2^+	52.4 %
for D_3^+	68.8 %
4. Reionization loss	
for D°(200 keV)	12 %
for D°(100 keV)	16 %
for D°(67 keV)	16 %
5. Beam divergence loss	10 %
6. Recovery efficiency for D^+(200 keV)	75 %

Table 3 The overall power efficiencies of a 200 keV INTOR injector

	without recovery	with recovery
Only D°(200 keV)	10 %	16 %
All neutral beams	13 ~ 17 %*	22 ~ 28 %*

*These spreads of values depend on how much power will be actually lost out of the totally produced secondary particles in the acceleration gap.

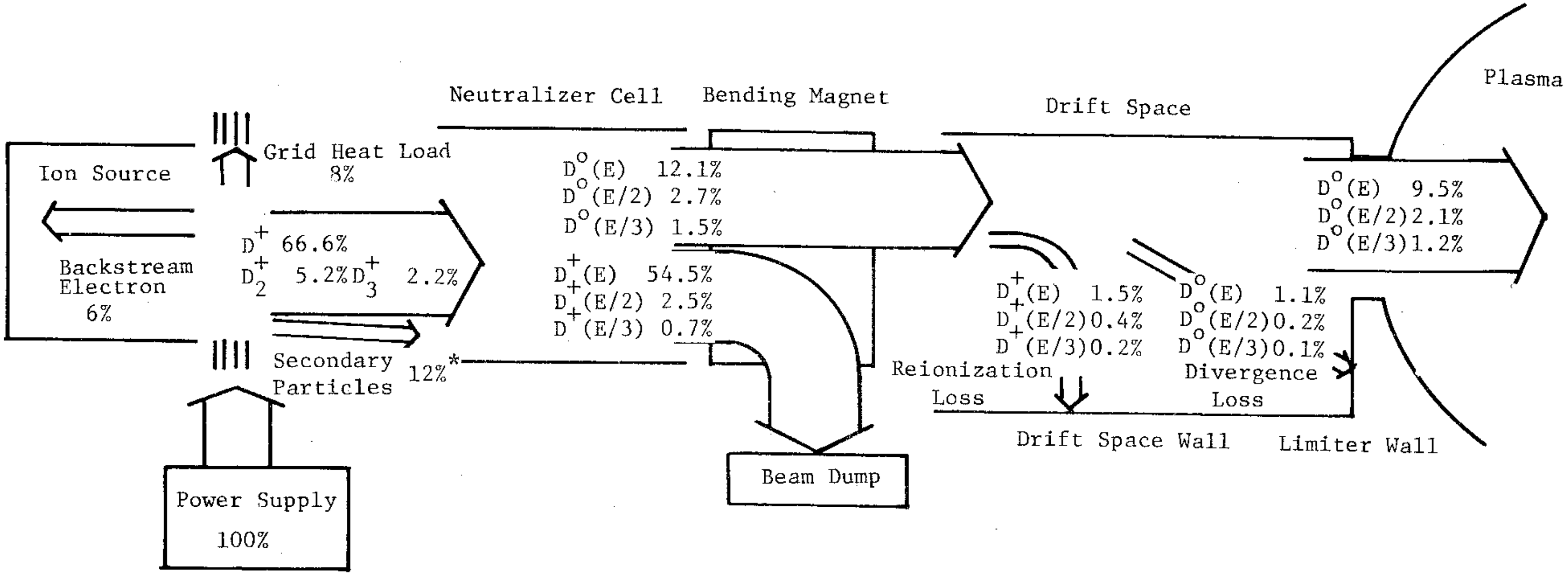

Fig. 1 The calcuration of neutral beam efficiency in the case without recovery system

* Destinations of these particles are not determined yet

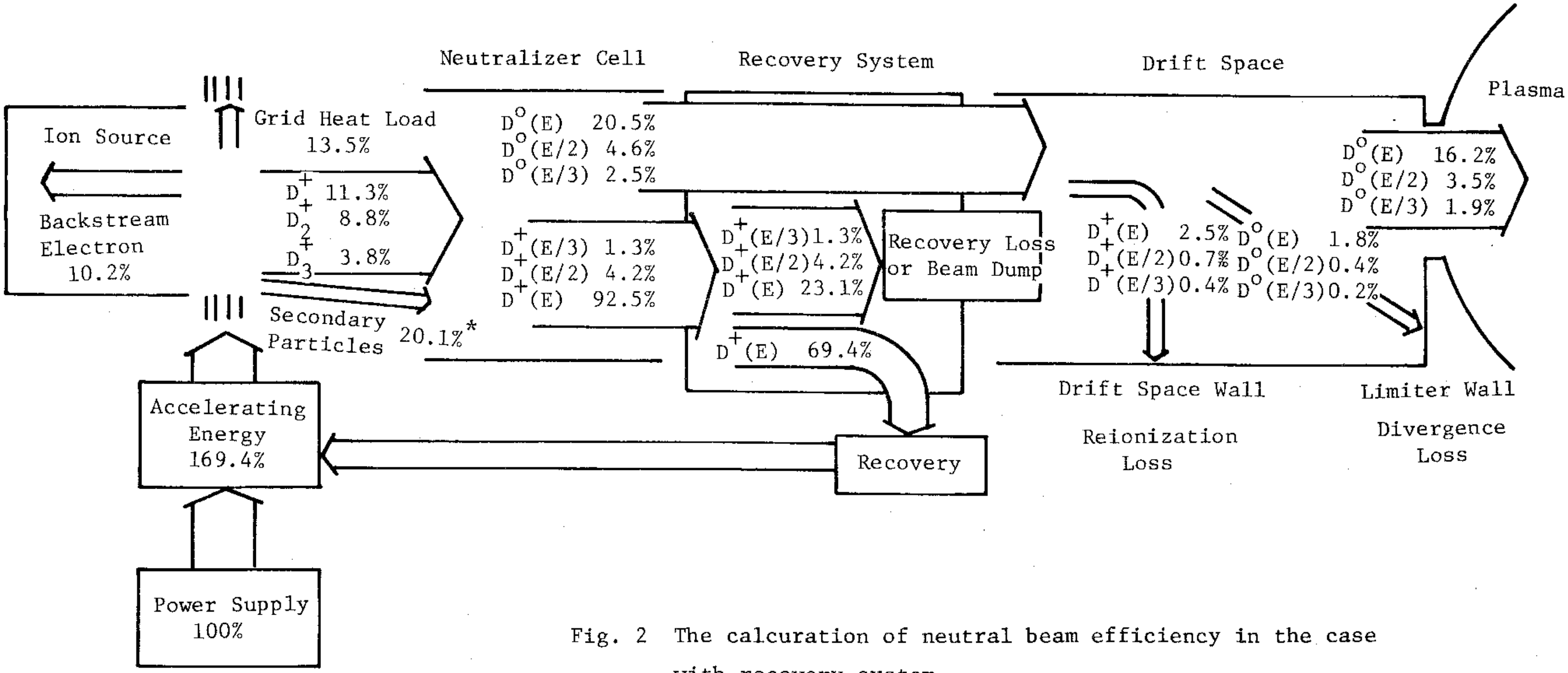

Fig. 2 The calcuration of neutral beam efficiency in the case with recovery system

* Destinations of these particles are not determined yet

(2) Pumping system shall keep the gas pressure in the energy recovery region less than 10^{-5} Torr.

(3) Tritium handling problem.

(4) The choice of cryo-panel materials enduring the neutron radiation damage.

(5) A pulse heat load to cryo-panel due to the cyclotron radiation emitted from tokamak plasma should be evaluated. In the JT-60, this pulse heat load to the port inlet is 6 kW and is reduced down to 25 W per one unit(1).

h. The need for negative ion beams

- Considering the neutral beam heating experiment in high plasma density regime, it will be necessary to develop the negative ion beam system.
- A study of negative ion source is at the preliminary stage in Japan.

i. Cold deuterium gas flow and impurities from the injector

- The cold gas flow into the plasma will be less than 3 Torr.l/sec (1×10^{20} particles/s) in the INTOR.
- The dominant impurities in neutral beams are oxygen and its hydrides. The amount of these impurities will be improved to 0.5 - 1 % in the INTOR.
- In the case of 7 cmϕ duoPIGatron source, the amount of impurities was 2.2 % of the total ion current.7)

j. Vacuum system needed in the neutral beam lines

- Cryo-condensation pump would be suitable in the INTOR.
- See 2.1.4, g.

k. Ion source development

- Several types of ion sources have been developed at JAERI. Present status and the specified values for JT-60 are shown in Table 4.

Table 4 Present status of ion source development at JAERI

Type	Extrction power	Pulse length	Grid area
duoPIGatron	75 KV x 5 A	10 s.	10 cm^{ϕ}
duoPIGatron	30 KV x 30 A	0.1 s.	18.5 cm^{ϕ}
Bucket	30 KV x 30 A	0.1 s.	18.5 cm^{ϕ}
Lambdatron	30 KV x 30 A	0.1 s.	18.5 cm^{ϕ}
Lambdatron for JT-60	75 KV x 35 A**	10 s.**	12 cm x 27 cm**

* see 3. 3.1

** the specified values

2.2 RF Heating

2.2.1 Experimental Status and Future Plans of RF Heating

A lower hybrid heating experiment has been made in JFT-2 with the radio-frequency power of 200 KW at 650 MHz and 750 MHz.[8,9] A phased array of four wave guides was used for launching the wave and the coupling efficiency was larger than 90 %. The ion heating increase was propotional to the input power at a rate of about 1 eV/KW. No significant adverse effect was observed on the global behavior of the plasma. Negligibly small electron density increase during rf pulse was observed in recent 150 KW experiment with titanium gettring of the vacuum vessel wall and the wave guide surface. The study of a heating mechanism is now under way.[10] ICRF heating experiment was also conducted in JFT-2a(DIVA).[11] Very recently substantial ion heating has been recorded (ΔT_i=270 eV,P_{rf}=180 KW) in two-ion regime.[12]

Lower hybrid and ICRF heating experiment programs are considered in JFT-2 or JFT-2M with RF power output of about 1 MW and lower hybrid heating in JT-60 with the power input of 10MW. In these experiments, wave propagation,power deposition and heating mechanisms will be studied extensively.

2.2.2 Lower Hybrid Heating in INTOR

Although non-linear effects were observed in the experiment of JFT-2, the effective ion heating was obtained when the turning point predicted by the linear theory existed in the plasma. So far the wave heating conditions can be reduced from the linear theory on the wave propagation and the power deposition.

From the accessibility condition of the LH pump wave and the reasonable design of the launching structure (phased array of milti-waveguides), it is appropriate to choose N_z between 2 and 4 for the expected INTOR parameters. The pump wave frequency should be chosen so that the wave power deposites near the plasma center. Since the Joule plasma densities in INTOR are presumed that $\bar{n}_e = 2 - 3 \times 10^{19}\ m^{-3}$, two sets of lower hybrid heating system are typically required to heat the Joule plasma to the ignition. These are the f = 1.5 ~ 2 GH_z heating system for $\bar{n}_e = 2 \sim 6 \rangle\ 10^{19} m^{-3}$ and the f = 2.5 - 3 GH_z system for $\bar{n}_e = 6 \times 10^{19} \sim 1.2 \times 10^{20}\ m^{-3}$. The first system is required the power input of about 10 MW and the second one has to deposite the power of 50 MW in the plasma.

The heating efficiency can be expected about 40% and the power density larger than 4 kw/cm^2 will be available at the top of the launcher. Then the wave-guide area at its top is 3 m^2 for the 50 MW power input, which permits a compact and easily accessible launcher.

2.2.3 Technological Assessment of RF Heating

a. RF System suited in a reactor environment

- From the generation and transmission of RF power, low frequency wave heating system is more available. However, high frequency wave heating system is more applicable since waveguide coupler will be used and easier to be replaced. Therefore, LHRF(lower hybrid range of frequencies) or ICRF(ion cyclotron range of frequencies) heating would be more suitable. In the ICRF case, a loaded waveguide launcher have to be developed in a reactor condition.

b. Launching structure

- Coupling coils inside the liner will be difficult to design in severe conditions of thermal input from the plasma. Waveguide coupler, so called Grill, is simple and more preferable. A theory is needed to design the launcher, just like a Grill theory of the lower hybrid wave heating.

c. RF power density

- More than 4 kw/cm^2 will be delivered in INTOR.
- In the JFT-2 lower hybrid heating experiment at JAERI, power density at 1.2 kw/cm^2 was handled in 1978. We observed ion temperature increase without any increase in electron density using a new type of waveguide coupler. Also 2 kw/cm^2 will be experienced in 1979 JFT-2 heating experiment and 3.5~4 kw/cm^2 in 1980~1981 engineering test of RF coupling system. We are now using the designing value of 3.5~4 kw/cm^2 in the JT-60 lower hybrid heating system.

d. Efficiency of a RF system

- The overall efficiency of an INTOR lower hybrid heating system would be 0.14~0.25. Efficiencies of components are used as follows:

Power supply	0.9,
Klystron	0.8(=0.5+0.5×0.6),
Transmitting system between	0.8~0.9,

klystron and coupler	
Coupling system	0.8~0.95,
Plasma heating	0.3~0.4.

- The most important efficiencies are those of klystron and plasma heating. As for the plasma heating efficiency we used a conservative value of 0.3~0.4. A higher heating efficiency should be developed before the construction of INTOR RF heating system.

  Also, we adopted a collector potential depression (CPD) for the collector of the klystron. It will be very interesting and useful to get a good efficiency of the klystron and probably inevitabe in case of multi Mw-long pulse klystron. From the disk model simulation,about 60% of the electron beam power passing through a output cavity is recovered using a three stage CPD collector. Therefore, if we assume 50% klystron efficiency 80% of final efficiency will be obtained. CPD techiqne should be developed relating with stability of the electron beam.

e. Reliability of the INTOR RF system

- Main troubles will be the reliability of klystron and launcher. However, JT-60 lower hybrid heating system of pulse length 10 sec and duty factor 1/60 will be developed at JAERI. Most of data required for the INTOR will be obtained.

3. Topics

3.1 Backstream Electron into the Arc Chamber of an Ion Source

The back plate in the arc chamber of the ion source is exposed to the high heat flux of the backstream electrons during the extraction of 200 keV D^+ beam. The production process of backstream electrons can be classified mainly into two types as follows;

(1) Production of free electrons in the accel gap by the collision of primary beam ions with residual cold gas molecules.

(2) Secondary electron emission from the surface of the suppressor grid due to the impingement of both slow ions produced by the ionization process and the charge exchange process, and the backstream ions from the gas cell plasma.

The flux depends largely on the cold gas pressure among the extraction grids. Figure 3 shows the dependence of the backstream electron power normalized by the total ion beams output on the gas pressure at the ion source exit as a parameter of the pressure in the arc chamber, where the ion accel voltage is 75 kV. At the 200 kV D^+ beam extraction, the power of backstream electrons to the arc chamber is calculated to be up to 7 - 8 % of the total beam output. When the beam current density is 150 mA/cm^2, the transparency of the extraction grid is 40 %, the source gas pressure is 5 mTorr and the gas pressure of the neutralizer cell is 3 mTorr, the heat flux of the back plate amounts to as high as 900 w/cm^2. Furthermore, the conventional ion sources such as the duoPIGatron or the bucket source which use a magnetic field for source plasma production would increase heat flux by focusing backstream electrons and will not be appropriate for INTOR purposes. Therefore, a careful design of the source plasma generator will be required for the high energy and quasi-DC beam production.

In JAERI, a new ion source with electron beam dump in the arc chamber (Lamdatron) is designed for the JT-60 neutral beam injector which can deliver an ion beam of 35 A with energy of 50 - 100 keV for 10 sec. (see Fig. 4) The beam dump is made of an array of cooling pipes shaped like a roof of the house, and is capable of handling the total electron heat loading up to 500 kw with a heat flux of 500 w/cm^2 maximum. The source will soon be tested.

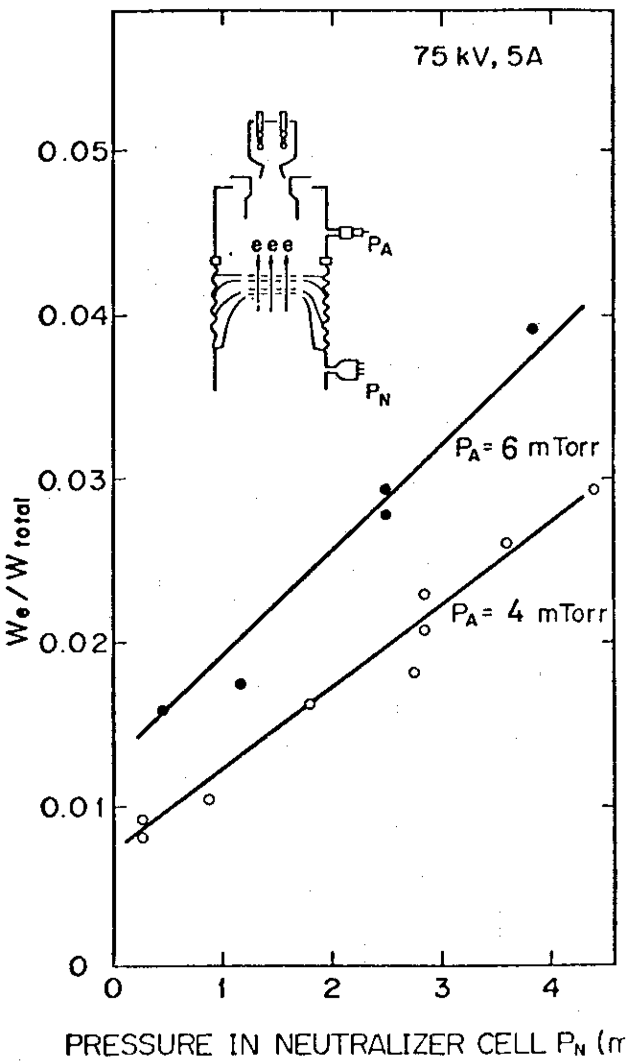

Fig. 3 Backstream electron power measured as a parameter of the pressure in the arc chamber.

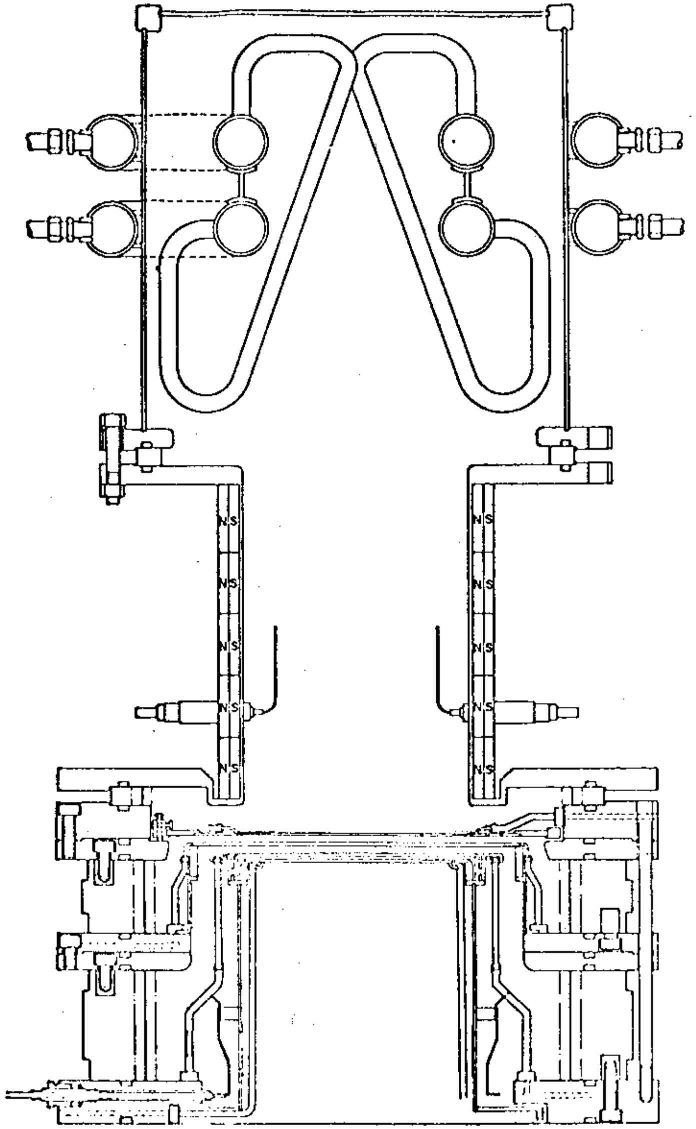

Fig. 4 Lambdatron (for JT-60)

3.2 Secondary Particles Produced in Ion Acceleration Region

The secondary particles are produced in the acceleration region by both the ionization process and the charge exchange process. The spectra of the secondary ions and neutrals are shown in Fig. 5 and Fig. 6 respectively, for a typical design value of the ion source. The energy spectrum of the neutral beam will be affected considerably by the large flux of these secondary particles. Yet we have'nt analyzed what fraction of the power out of these secondary particles will actually be lost due to their divergences. The effect of these particles should be included in the design.

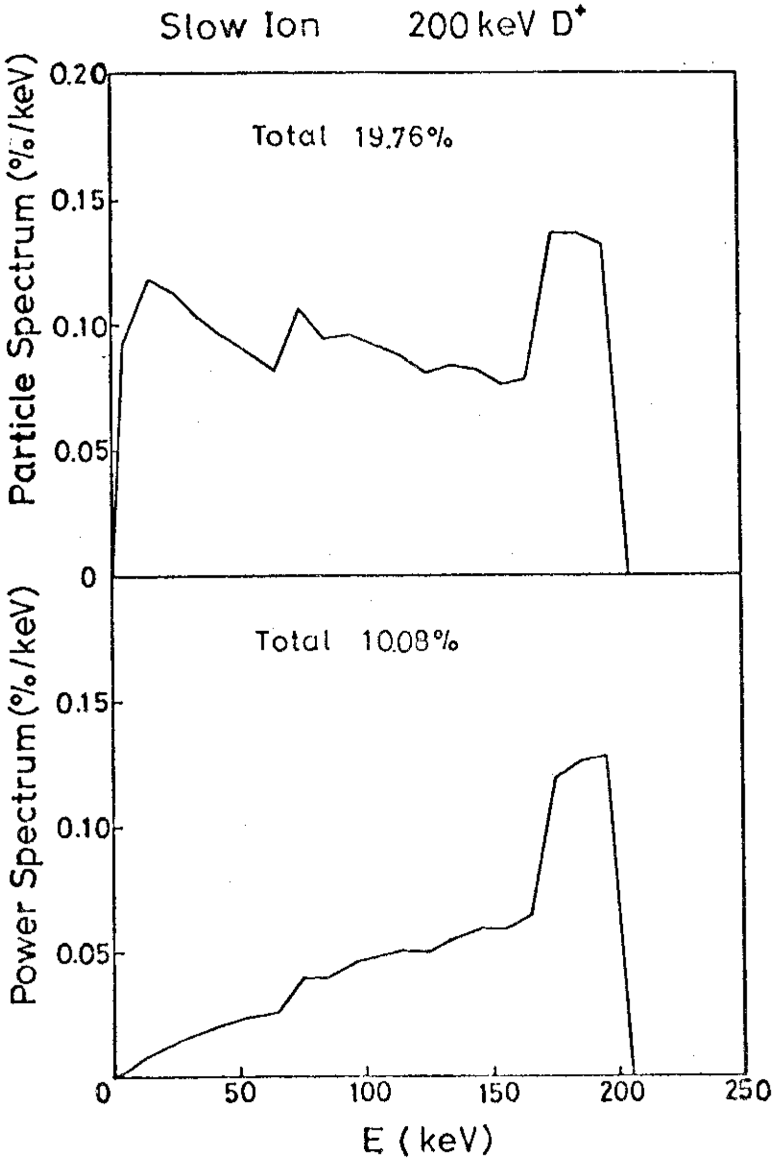

Fig. 5 Power and particle spectra of secondary ions

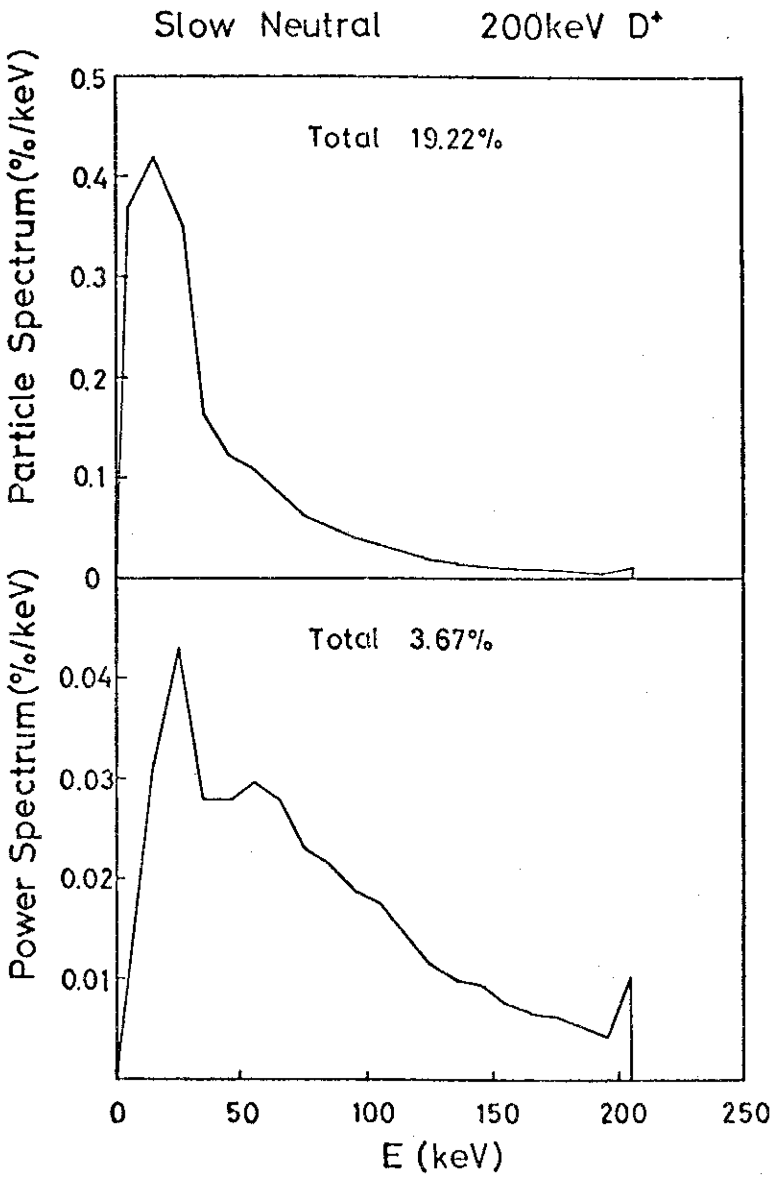

Fig. 6 Power and particle spectra of secondary neutrals

4. Research and Development Needs

(1) Neutral beam heating

Items	status*
① Development of a long pulse ion source · plasma source (cooling) · accelerating grid (cooling) · filament (long life)	1)
② Cooling of a beam target and a ion beam dump	1)
③ Direct recovery • increase an efficiency of a recovery system · direct recovery grid (cooling)	2)
④ Pumping problems · new neutralizing method such as gas jet stream	2)
⑤ Negative-ion beam system	2)
⑥ Radiation hardening problem	3)
⑦ Remote handling	3)

* 1) existing programme is adequate.
2) existing programmes, but inadequate.
3) no existing programme.

(2) RF heating

Items	Status
① Development of long-pulse klystrons of 1 MW or larger for JT-60 LH(lower hybrid) heating system	1)
② R & D efforts on the rf coupling system of LH and ICRF heating for the INTOR	2)
③ 1 or multi-MW LH heating experiment	2)
④ 1 or multi-MW ICRF heating experiment	2)
⑤ R & D of long pulse 1 - 5 MW sources for ICRF heating system	3)
⑥ R & D on the high power and long pulse gyrotron	3)

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